A revised strategy for the monitoring and management of the Galapagos sea cucumber *Isostichopus fuscus* (Aspidochirotida: Stichopodidae)

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Abstract: The brown sea cucumber fishery is active in the Galapagos Islands since the year 1991 after its collapse in mainland Ecuador. This paper analyzes the Galapagos Sea cucumber fishery over the past decade and the reasons for its management pitfalls and chronic over fishing, and proposes an improved strategy for estimating stock size and harvest potential. Based on the historical distribution of the fishing fleet and past fishery surveys, 15 macrozones were defined; their areas were estimated from the coastline to the 30m isobaths and the numbers of sample replicates per macrozone were calculated for a density estimate precision of ±25%. Overall stock size was calculated by summing over all macrozones and was multiplied by 0.122 to obtain the annual quota. This multiplier was derived by inserting an exploitation rate of E=0.3 and a published natural mortality value of M=0.17 into Cadimas formula, thereby obtaining a more conservative precautionary quota estimate. Pre-fishery stock densities in 2009 were below the legal threshold value and the fishery remained closed. Mean densities were significantly lower in the deeper (>15m) than in the shallower (<15m) stratum, contrary to fishermen expectations. Through an empirical regression of (log) pre-fishery density versus subsequent annual catch for the period 1998-2008 we found that catches of most years greatly exceeded the here proposed quota explaining the collapsed nature of the stock. Rev. Biol. Trop. 60 (2): 539-551. Epub 2012 June 01.

Key words: Galapagos, invertebrates, over fishing, quota, sea cucumber.

The small scale fishery of the brown sea cucumber (*Isostichopus fuscus,* Ludwig, 1875), one of the most commonly found species in the Eastern Pacific (Maluf 1991), started in the Galapagos Islands in 1991 after its fishery collapse in mainland Ecuador (De Paco *et al.* 1993, Powell & Gibbs 1995, Martinez 2001). A fishery based on this species lasted only six years in Baja California (Aguila-Ibarra & Ramirez-Soberón 2002). The Galapagos pepino diving fishery operates in shallow waters of usually less than 30m depth. Of a total number of 1 032 fishermen presently registered, the number involved with the sea cucumbers has greatly varied over the years (Castrejón 2009). During the most recent season (2009) less than 30% of registered fishermen have participated in the fishery.

After the start of the fishery in Galapagos, catches rose and during the "peak period" 1999 to 2005 almost 30 million sea cucumbers were harvested legally within the Galapagos Marine Reserve (GMR) corresponding to a total fresh weight of >8 000t. Catches peaked in the year 2002 with over 8.3 million individuals (Fig. 1), but continuously decreased thereafter. During the fishing season of 2008 only about 0.86 million individuals were caught, although a total

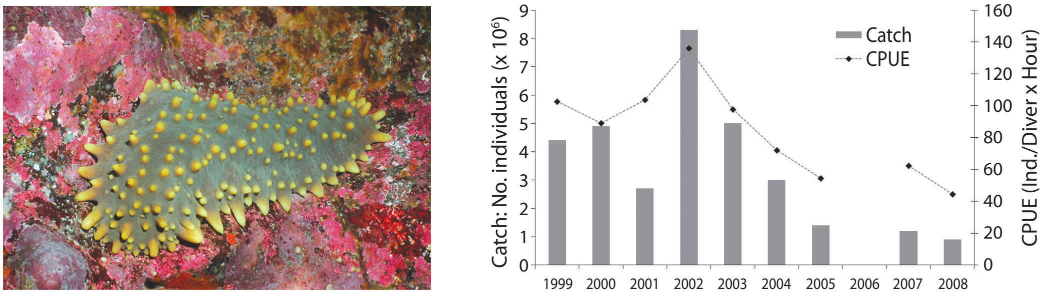

Fig. 1. Left: the Galapagos sea cucumber *Isostichopus fuscus* (image of Diego Ruiz); right: catch in number of individuals and catch per unit of effort (ind./diver x hour) for the period 1999-2008 from CDF fisheries reports (the 2006 fishing season was closed).

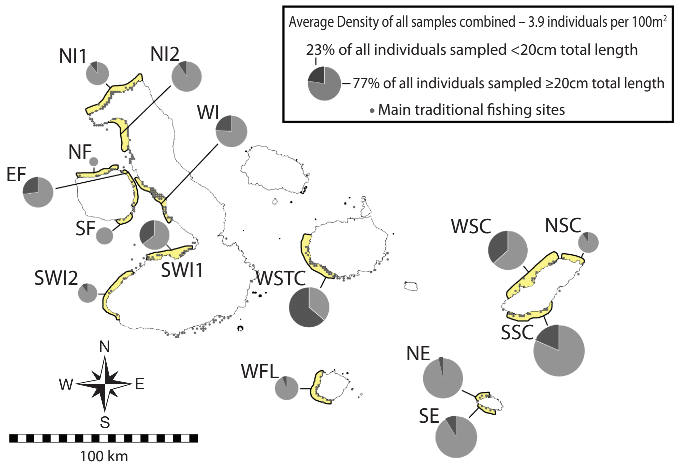

Fig. 2. Main traditional sea cucumber fishing sites as assembled from geo- referenced onboard and landing sites registries (2001-2008) from CDF and PNG data bases. Location and extension of 15 macrozones identified (abbreviations in Table 1). The area of each pie chart represents mean density per macrozone of 2009 pre-fishery sea cucumber monitoring divided into percentage of individuals smaller then 20 cm and larger than 20 cm total length. Pie chart in legend represents overall mean value of all macrozones combined. *50% of total area.

allowable catch (TAC) of 1.3 million had been agreed upon by the Participatory Management System (PMS), which is in place in Galapagos since 1998. The great decrease in catches after 2002 is generally explained by strong over fishing, driven by a Chinese market, where this species is appreciated and of high market value (Toral-Granda 2008). The boom and bust situation of the Galapagos sea cucumber followed by a prolonged period of a very low stock sizes, has also been described for many other sea cucumber species worldwide (Conand 2004, Uthicke 2004). This seems at least partly due to the fact that most species are fairly slow growing with low population productivity and great vulnerability to overfishing (Toral-Granda *et al.* 2008).

Isostichopus fuscus is gonochoric, but does not display sexual dimorphism. Fifty percent of individuals from Galapagos attain sexual maturity at 23.6cm, although individuals of 16cm with developing gonads have been recorded

(Toral-Granda 1996). Reproductive activity occurs throughout the year and is thought not to be affected by temperature in the Galapagos Islands (Toral-Granda 1996); while in Mexico, increased reproductive activity was observed in the warm water season (Herrero-Perézrul *et al*. 1999). Larvae are planktotrophic (Toral-Granda 1996) and transparent, and display indirect development (Hamel *et al*. 2003). Under laboratory conditions, metamorphosis and settlement of 1mm juveniles can occur 28 days after fertilization (Hamel *et al.* 2003). Herrero-Perézrul *et al*. (1999) obtained preliminary population parameters of *I. fuscus* from Mexico, which included estimations of asymptotic length ($L\infty$=36.118cm) and growth coefficient (K=0.180/yr). In a later study, Reyes-Bonilla & Herrero-Perézrul (2003) obtained a smaller infinite length and a higher k-value ($L\infty$=29.108cm, K=0.243/yr). These growth parameters suggest a life span of this species between 12-17 years.

The starting fishery was centered in Western Isabela and Fernandina (Fig. 2), where population densities were highest. A pilot population study off Fernandina in 1993 yielded a mean density of 6.24ind./m^2 (Aguilar *et al.* 1993), and later assessments recorded between 0.8-6.2ind./m^2 in the Canal Bolivar area (Aguilar *et al.* 1993, Richmond & Martinez 1993). A stock depletion model run in this area (Hearn *et al.* 2005) yielded initial densities of adults (>16cm TL), between 0.27-0.40ind./m^2 from 1994 to 1997, similar to those obtained in 1999 (Toral-Granda & Martinez 2004). Currently, densities have decreased by about an order of magnitude to 0.03ind./m^2 (Murillo *et al.* 2008, this study).

A strong recruitment event of the *I. fuscus* population in Galapagos was registered in 2000 in the Canal Bolivar area (Murillo *et al.* 2002, Hearn *et al.* 2005), which ended in 2002.

The steadily decreasing catches of the sea cucumber fishery over the past decade (following the peak of 2002), are mainly the results of a chronic over fishing that has not allowed the stock recuperation (Hearn *et al*. 2005). The main reasons are an overcapacity of the fleet, a reactive instead of proactive management, and a 'race for fish' situation, the lack of control as well as difficult enforcement of the fishery regulations in this large archipelago with far away fishing zones, which also leads to illegal fishery. In addition to these problems, the determination of an annual quota by the managers of the marine reserve and the scientists involved, had not been derived from stock size estimates and scientific reasoning about an acceptable fraction of the annual stock to be harvested. Instead, the quota was negotiated by the co-management system in place (except for the boom year of 2002). Only in 2009 a limit reference point (LRP) of 11ind./100m^2 was implemented and the fishery may only be opened once the stock density in the principal fishing area of Isabela as derived from the pre-fishery monitoring is above this reference value (Comisión Técnica Pesquera de la Junta de Manejo Participativo 2009). LRP reflects the lower end of a mean density range (11-20ind./100m^2) observed during historical surveys and characteristic for a stock in recuperation. Below this density interval the stock is considered to be in a critical stage, above in a healthy stage (Castrejon *et al.* 2008). These measures caused two problems. The first was that fishermen preferentially monitored areas, where densities had traditionally been above average, not representing the overall mean density of all macrozones. The second problem was that once the fishery was opened, fishermen would take out all adult sea cucumbers (>20cm total length), that they could find within their economic constraints. In years, when quota was negotiated, there was a lack of an adequate stock monitoring design and the poor information available did not allow for a precise quota calculation. As a result the quota was usually too high with the result that the remaining post-fishery stock was extremely small, lacking the potential for biomass to rebuild up to the next year's fishing season. Due to these problems associated with the management of the Galapagos sea cucumber fishery, we aimed to improve the monitoring and management strategy.

Our research goals were to: (1) optimize stock evaluation procedures by considering macrozone differences in density and stock distribution, and (2) to provide a scientific basis for the estimation of an annual quota. Specific research questions addressed were: a) are there spatial-temporal differences in sea cucumber densities within the fishing area, for the period 1999-2009, which would allow to classify key areas/macrozones of sea cucumber distribution in the archipelago? b) Is there an observable spatial-temporal trend in sea cucumber size distribution? (i.e. are there macrozones and years of higher numbers of recruits?) c) Are stock densities higher in deeper (>15m) than in shallow (<15m) waters as suggested by fishermen? d) Can we derive an estimate on stock productivity based on available literature, which allows for the calculation of a reasonable catch quota from annual estimates of stock size?

MATERIAL AND METHODS

Estimation of fishing areas (macrozones): The design of the new monitoring plan was derived from information of past monitoring surveys carried out annually from 1999 to 2008. Two types of monitoring had been carried out, pre-fishing and post-fishing. Since the pre-fishing data were generally more complete and consistent (Vadas 2008), we decided to focus on those for the analysis. The monitoring effort of all years was aimed to cover the principal fishing areas as well as no-fishing areas. This resulted in very large areas and for several of them in wide confidence limits around the density estimates.

The first 19 macrozones for the islands of Fernandina, Isabela, Española, Floreana, San Cristóbal and Santa Cruz were defined considering the principal sea cucumber fishing zones as derived from fisheries statistics of the PNG and CDF of the period 2001-2008. Due to insufficient financial resources and because fishermen insisted that four of the previously defined macrozones (east Santa Cruz, East and South-East Isabela and East Floreana) are not currently used as fishing zones, the macrozones surveyed in this study were reduced to 15.

Each macrozone was delimited using georeferenced catch data from the participative monitoring programme conducted during this period by the following procedure: bathymetric data compiled by Chadwick (1994) for the depth range from 0-1 500m depth, as well as from the CDF Geographical Information System (coastline CDF/Clirsen-TNG/GNPS) data from 0-39m were subjected to an ArcGIS Triangulated Irregular Network (TIN) interpolation routine, which creates circumcircles around each selected sample point and their intersections are connected to a network of non overlapping triangles, being as compacted as possible. Based on this interpolation a -30m isobath, which is the maximum depth where fishing can be carried out, was created. With the isobath line as the outer and the coastline as the inner boundary, the area of each polygon (m^2) was mapped. A histogram was created to describe the frequencies of points per depth strata and an analysis was done to describe mean distances between points by using nearest neighbor statistics (ArcGIS and Surfer). Only 50% of the estimated area was considered as suitable sea cucumber fishing area and habitat, given that approximately 20% has unsuitable sandy bottoms and another 30% is too shallow (<5m intertidal waters), or uninhabitable steep slopes (Banks *et al.* 2006).

Determination of transect number per macrozone: In order to estimate the required number of transects per macrozone, we proceeded as follows: first, means and standard deviations of stock densities obtained during past surveys were calculated for each zone. Then, 95% confidence intervals around the mean stock densities were estimated for each zone and 95% confidence intervals around the mean stock densities were calculated; second, the homogeneity/degree of patchiness of sea cucumber distribution per macrozone as reflected by those statistics was then used to calculate the minimum number of replicates necessary per macrozone to achieve a precision of ±25% applying the following formula:

$$n = \left(t_{(n-1)} * \frac{SD}{0.25 * Av} \right)^2$$

with n=minimum number of replicates required to achieve a precision of ±25% around our estimate of mean density; t=value of the t distribution (student's t-test) for $p<0.05$; Av=annual average of the sea cucumber density per macrozone and SD = standard deviation.

Using the above formula, differences in spatial distribution and stock density per macrozone resulted in different numbers of replicates required for the different areas, with more replicates for areas of higher patchiness, and lower numbers where the population appears more evenly distributed. Based on this procedure population size estimates are considered substantially more precise than if the replicate number was just proportional to the size of the area.

Sampling: The type of sample unit used was a circular transect with a radius of 5.6m which covers an area of 100m^2. This has been used in monitoring activities before and has proven to allow for the collection of available sea cucumbers with low error (Hearn *et al.*2005). Moreover, using this sample unit unbiased comparisons with previous surveys became possible. The exact location of each transects in each macrozone was decided jointly between fishermen and scientists with the aim to adequately cover each area. The sampling sites were distributed in two depth strata: shallow (<15m) and deep (>15m), with the shallowest and deepest waters around five and 25m respectively.

The stock size per macrozone was estimated extrapolating the mean density value (ind./m^2) to the corresponding total area. Then, the stock sizes of each macrozone were added up to estimate the stock for the whole fishing area.

The mean density value within the West Isabela macrozone was then compared with the sea cucumber reference points defined in the Fishery Chapter of the Management Plan for the Galapagos Marine Reserve (GMR) (Castrejon *et al*. 2008, Comisión Técnica Pesquera de la Junta de Manejo Participativo 2009). According to these reference points a healthy, abundant stock should have a West Isabela macrozone density >21ind./100m^2, while densities of a stock in recuperation should range from 11-20.9 ind./100m^2. If densities are <11ind./100m^2, the stock is closed for fishing.

Precision of density estimates and density comparisons between depth strata: Since the density values of each macrozone proved to be not normally distributed, a bootstrap resampling routine (Efron 1981) was applied, which consisted in a random resampling (1000x) of the data matrix for each macrozone. This yielded 1000 normally distributed mean density values and allowed for the computation of the standard deviation and coefficient of variation (CV%) around the mean of these values.

In order to test for depth strata differences in sea cucumber densities, all density measurements taken in each depth stratum (shallow and deep), were considered for the calculation of overall means per depth strata. The resulting mean densities were bootstrapped for each depth stratum and compared using a t-test of means. For comparative purposes also a non-parametric Mann-Whitney U test for the medians was applied. We repeated this analysis by combining the information of sea cucumber density per depth strata for all those years where sufficient samples had been taken (1999-2002 and 2006-2009).

Calculating the catch quota. Annual stock production can be calculated by multiplying mean stock size by the rate of total production (P/B=Z) which is the sum of natural (M) and fisheries (F) mortalities. P/B tends to increase with fishing pressure while the stock biomass decreases. Gulland (1971) and Garcia & Le Reste (1981) proposed to approximate the maximum sustainable yield (MSY) of a stock from an estimate of its virgin biomass (B∞) and the rate of natural mortality (M). They propose: MSY = X* M*B∞ (With X=0.5 in the formula of Gulland and in the range of 0.32-0.44 in the formula of Garcia and Le Reste respectively). If a resource is heavily exploited and virgin stock levels can not be determined this formula should not be applied. Cadima (in Troadec 1977) proposed to use the following formula instead:

MSY=0.5 *Z *B, where B is the current stock biomass.

This formula is identical to MSY=M*B, if F=M at an exploitation rate of E=0.5.

Garcia *et al.* (1989) pointed out that Cadima's formula only gives unbiased estimates of MSY if the stock is virgin and Z=M (when it is identical to Gullands formula mentioned above) or when the stock happens to be exploited at the level of MSY already (at $B\infty/2$ and an exploitation rate of 0.5).

Considering this reasoning of the above authors and assuming that the current stock level of the Galapagos Sea Cucumber is far below $B\infty/2$ it was decided to use a lower (precautionary) exploitation rate of E=0.3 when applying the Cadima formula. The M- value (0.17/year) of Hearn *et al.* (2005) was used, which was derived from a stock depletion model. This value was based on a rich data source and appears as a sound estimate in the right order of magnitude, when compared to other slow growing marine invertebrates reported in the literature (Brey 2001). A value double as high for this species in Mexico (M= 0.354/year) was proposed by Reyes-Bonilla & Herrero-Perézrul (2003), who, however used empirical formulas for its derivation, which were not established for holothurians.

Considering this M value of 0.17 the F value was calculated corresponding to an exploitation rate of E=0.3 by calculating:

F/Z=0.3;
F=0.3(0.17+F);
F=0.051+0.3F;
F(1-0.3) =0.051;
F=0.073;

By inserting the F and M values in the Cadima formula (above), we arrived at:

Quota ("MSY")=0.5 (0.073 +0.17) *B
Quota = 0.122 * B;

The annual quota here proposed is thus 12.2% of the standing stock.

RESULTS

Estimates of macrozone areas and number of transects per macrozone: Figure 2 shows the distribution of sea cucumber fishing activities in the archipelago for the years 2001 and 2008 and the 15 macrozones using these data. Table 1 gives their extension and the numbers of replicates per macrozone required for a mean stock density estimates <±25% precision. It also provides the density estimates and quota per macrozone derived from the monitoring survey of 2009. The overall estimate of fishable area of all macrozones combined is 124.8km^2.

The population monitoring was carried out in the last two weeks of May 2009 by fishermen, National Park and CDF staff coordinated and financed mainly by the National Park. San Cristóbal is the island with the largest fishing area (52km^2), followed by Isabela (33km^2) and Santa Cruz (20.4km^2). Floreana, Española and Fernandina combined only represent 20km^2. While the coastline of Isabela where fishing takes place is much larger than the one of San Cristóbal, the fishing area is smaller due to the very steep slope bringing the -30m isobath much closer to the coastline in Isabela than in San Cristóbal. It is interesting to see that replicate numbers vary greatly between zones with Española requiring the highest number per area (49/5km^2), while Santa Cruz requires only 31 transects in 20.5km^2.

Densities and catch quota for the season 2009: Mean density for West-Isabela (3.72ind./100m^2) is far below the critical value for the opening of the fishery (11ind./100m^2)

TABLE 1
Macrozone surveys and quota calculations

Island	Macrozone	Abbr.	Area*	MD	TNp	TNc	CV (%)	Quota
Isabela	Combined		32.8	3.19	179	125	11.59	127 651
	North Isabela 1	NI1	1.6	2.79	25	10	25.00	5 446
	North Isabela 1	NI2	3.6	3.62	19	21	25.00	15 899
	West Isabela	WI	4.0	3.72	55	40	21.62	18 154
	Southwest Isabela 1	SWI1	13.3	3.58	57	24	25.00	58 089
	Southwest Isabela 2	SWI2	10.3	2.22	23	30	27.27	27 896
Fernandina	Combined		6.3	2.01	49	35	24.90	15 449
	North Fernandina	NF	1.5	1.00	10	11	70.00	1 830
	East Fernandina	EF	4.5	3.51	8	20	25.71	19 270
	South Fernandina	SF	0.3	1.51	31	4	81.25	553
Santa Cruz	East Santa Cruz	WSTC	20.4	4.80	31	25	22.82	119 462
Floreana	West Floreana	WFL	8.5	2.05	32	26	22.14	21 259
San Cristóbal	Combined		51.7	4.43	119	97	13.26	279 418
	West San Cristóbal	NSC	10.5	2.40	47	5	58.33	30 744
	North San Cristóbal	WSC	31.8	4.73	14	56	18.75	183 505
	South San Cristóbal	SSC	9.3	6.15	58	36	19.67	69 778
Española	Combined		5.1	4.79	49	39	9.67	29 803
	North Española	NE	3.0	4.66	28	12	19.15	17 056
	South Española	SE	2.1	4.92	21	27	12.24	12 605
All Island	Combined		124.8	3.94	459	347	6.81	599 889

Abbr.=abbreviations of macrozone names, Area*=total effective fishing area representing 50% of total area, MD=mean density values of all macrozones, TN=transect numbers, CV=coefficient of variation in %, Quota=calculated in number of individuals (12.2% of total), TNp and TNc=planned and realized transects, respectively.

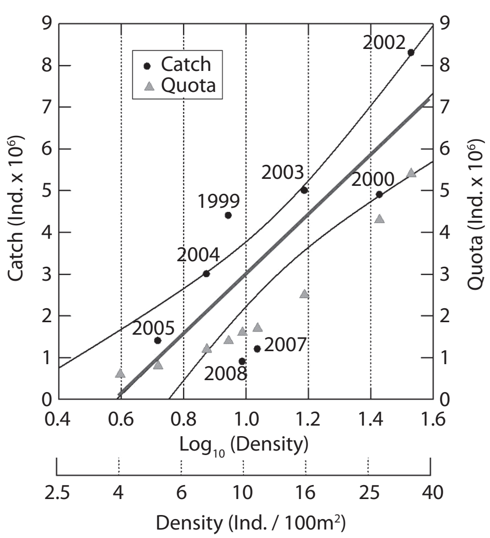

Fig. 3. Regression and 95% confidence interval of catch versus pre-fishery population density (ind./100m^2) from 1999-2008 (equation: catch = 7.22x(log density)-4.229, R^2=0.63, $p<0.05$) (data of 2001 were excluded due to an individual quota system applied during this year); triangles represent the quota that would have been calculated for those years if based on the pre-fishery densities and the 12.2% of stock size as presented in this study.

and was de lowest ever recorded in the last decade (Fig. 3). So, following the decision rule in place, it was recommended not to open the fishery for the year (2009). This recommendation was thereafter accepted by the co-management body (Interinstitutional Management Authority, IMA). The densities of all macrozones with the coefficient of variation around the mean (CV, %) are given in Table 1. If our rationale for a quota (TAC) estimate based on the stock size (4.9 million individuals) derived from the overall mean density (0.039ind./m^2) and our combined area estimate (124.8km^2) had been followed, the TAC would have been 59 889 individuals for the 2009 fishing season for the whole archipelago.

Figure 4 shows the mean densities (left) and the proportion of small (<20cm) sea cucumbers in the samples (right). Floreana, Isabela and Fernandina show a steady density

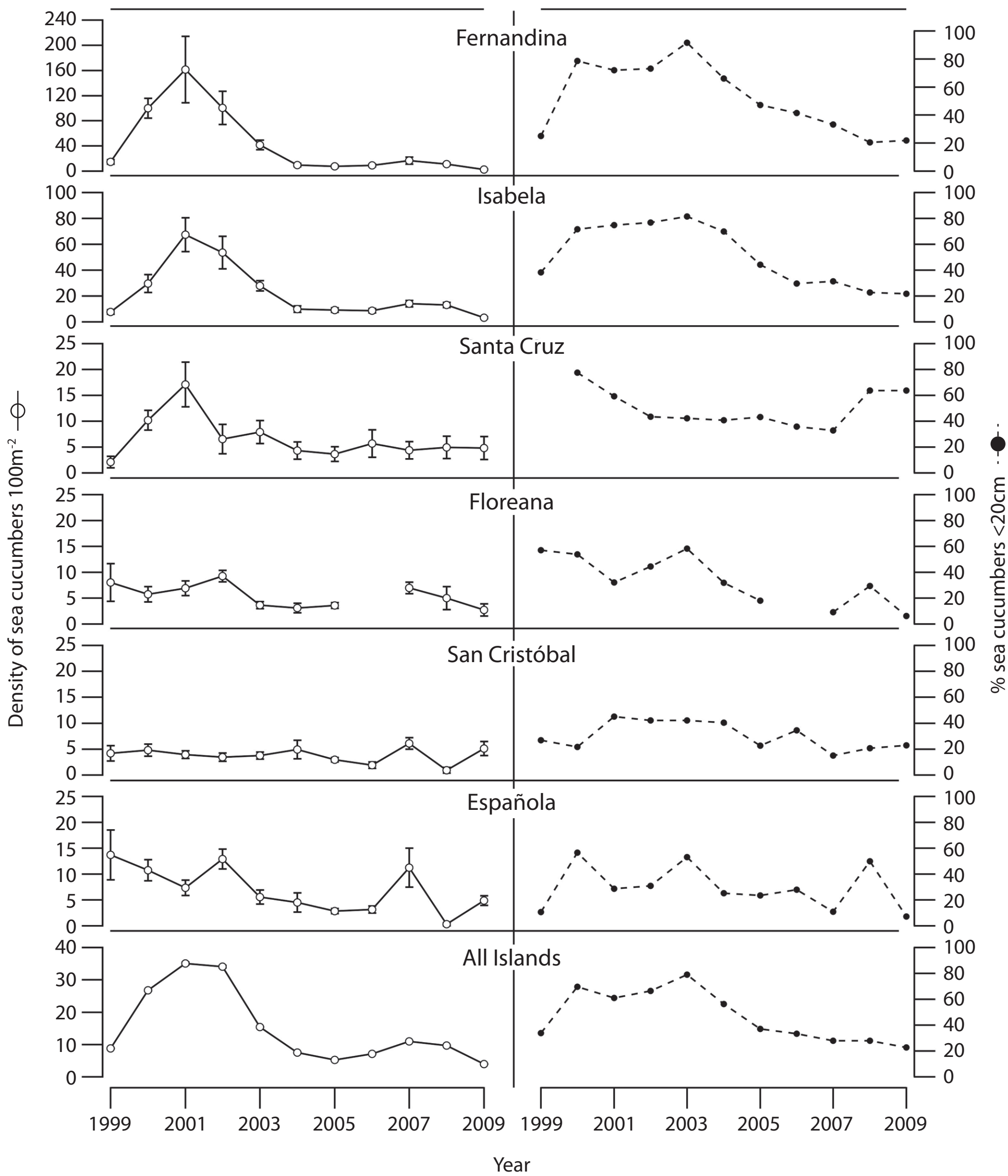

Fig. 4. Left: pre-fishery monitoring mean densities (ind./100m^2) from 1999-2009 for each island (bars indicate 95% confidence intervals around the mean); right: percentage of individuals <20 cm in total length separated per islands (1999-2009).

decrease over the past years, while Santa Cruz has remained quite constant over the past six years. The density value of San Cristóbal in 2009 was surprisingly the second highest since 1999.

The proportion of juveniles (recruits) in the stock has steadily decreased for the Western islands Isabela and Fernandina and is the lowest ever recorded in Española and Floreana. Santa Cruz and Cristobal revealed a slight increase over the last three years.

The 2009 monitoring data for the two depth strata showed higher densities in the shallow stratum compared to the deep stratum (4.5 compared to 3.2ind./100m^2 respectively). Statistically, this difference was significant if the non-parametric Mann-Whitney U test of the median density values was used or if the mean values using the bootstrapping routine were compared (t-test, $p<0.05$). The density difference between depth strata was even more pronounced, when the data of eight years was combined (8.7 versus 17.9ind./100m^2 for deep and shallow strata respectively).

DISCUSSION

This study is the first in trying to estimate the fishing area of the sea cucumber stock of Galapagos, which seemed imperative if overall stock size was to be approximated for quota calculations. Since the topography and slope of the sea bottom varies substantially between macrozones, and available bathymetric data points were not covering all areas uniformly, the mapping of the polygons between the coastline and 30m isobath using ArcGIS required an interpolation procedure. The TIN interpolation used to define the -30m isobath for our 15 macrozones was supported by 8 615 geographical data points over the depth range from 0-1 500m, of which a large proportion (3 228 points, 37.5%) were situated within the macrozone depth limits. Based on a nearest neighbor analysis, a separation value for the mean distance between points was found equal to 0.0031589 with a standard deviation of 0.0054607 (degrees).

While we believe that our first fishing area estimate is a good approximation, it can definitely be improved through a more detailed bathymetric survey of the coastlines of the Galapagos Archipelago.

The assumption was then made that of the estimated area 20% is unsuitable sandy bottom habitat and 30% too shallow (<5m) intertidal water or comprised by too deep waters (>25m) or inhabitable steep slopes. These assumptions are derived from a decade of sub-tidal macrofauna monitoring, as well as specific pre-and post-fishery monitoring reflecting a sufficient amount of data and the best estimate available for this study. It should be stated here, that the Ecuadorian Oceanographic Institute (INOCAR) has already started to conduct a mapping of the whole Galapagos coastal sub tidal areas using side scan sonar technology. We expect to soon be able to update our here presented estimates based on this information.

Only 383 out of 547 planned transects (70%) could be carried out during the 2009 pre-fishery monitoring due to financial constraints. However, this transect number is the highest ever used in the Galapagos sea cucumber pre-fishery monitoring (the second highest was 303 transects taken in the year 2008). The precision around the mean densities differs between macrozones with a coefficient of variation (CV) ranging from 12.2% for Eastern Española (n=27/a=2.1km^2) to 81.2% for Southern Fernandina (n=4/a=8.5km^2). These differences can be attributed to the number of transects and the degree of patchiness of the sea cucumbers in each zone. When the transect data are integrated for each island, the respective density estimate is greatly improved with CVs always <25%. The two islands that had the highest transect numbers (Isabela with 125 and San Cristóbal with 97) had the lowest CV around the mean density estimate (11.6% and 13.3% respectively). The density estimate for all transects combined (3.94ind./100m^2, CV=6.8%) can be considered of a very good precision. The great differences in densities and stock aggregation found between areas have been emphasized as being symptomatic for sea cucumber populations in general. Hand & Rogers (1999) summarized this problem by pointing to the variable spatio-temporal distribution of sea cucumbers, which make random surveys and conventional statistical approaches inappropriate. They also argue for the collection of ancillary information, such as substrate type to increase the precision of density estimates and for the use of geostatistical analysis and GIS to map the sea bed for benthic invertebrates. In our study, we followed the reasoning of these authors and our statistical analysis suggests that our macrozone and overall density estimates are good in general. However, some directed sampling has possibly occurred since fishermen often argued for sampling in those areas, where they had found sea cucumbers in previous years, sometimes not permitting full random sampling in each macrozone.

Of all macrozones sampled, none reached the minimum density of 11ind./100m^2 to open the fishery, which points to a very critical state of the stock in all macrozones. Several factors may explain this situation. During years 1999-2002 the seasonal fishery was opened without quota limits, and the stock was depleted to extreme low densities, not keeping a large enough residual biomass for the next season. In years, when catch quota were determined through the co-management process, these were often too high, representing too large a part of the available stock. This may be illustrated by the example of the year 2004, when a mean density of 7ind./100m^2 was counted during the pre-fisheries monitoring and a catch quota of three million individuals was agreed upon, 2.5 times the number which would have been estimated considering the reasoning of this study (12.2% of 8.73 million individuals, which are only 1.06 million). The general problem was that the quota was set with no available estimate of absolute stock size.

The density and recruit fraction trend over the past decade, suggests a further reason for the critical state of the stock: a lack of substantial recruitment during the past decade of predominant cold waters. Since the strong El Niño 1997/98, which seemed to have improved recruitment of sea cucumbers to the fishery during the years 2000-2003, sea surface temperatures (SST) around the Galapagos archipelago have remained quite low for most of the time representing an extended La Niña cold regime (Wolff 2010; see also SST data base of CDF on www.cdf.org.ec). So it may well be that in addition to the problem of a too small spawning stock remaining after each fishing season, spawning activity as well as larval and pre-recruit survival, may have been comparatively low during these years. Unfortunately, as yet little is known about the environmental window for optimal reproduction and early life stages development of this species. The strongest reduction in recruit proportions within the monitoring surveys over the past years was found in the Western islands Isabela and Fernandina, which were strongly exposed to cold upwelling waters during the past years of La Niña regime. The El Niño 1997/98 warming, on the other hand, seem to have caused strong recruitment in these areas, leading to enormous stock densities during the post-El Niño years 2000-2003. This positive El Niño warming effect on the recruitment of *I. fuscus* was first published by Herrero-Perézrul *et al.* (1999). Santa Cruz is the only island, where the fraction of small specimens <20cm seem to have increased over the past years 2008 and 2009. However, since mean density has not increased in parallel, this relative increase in small specimens is rather a sign of heavy depletion of larger adults than of a successful recruitment. In Española a density increase during the year 2007 was paralleled by an increased fraction of small specimens, which may suggest a small recruitment here.

In this report, an empirical relationship between the pre-fishery (log) density obtained through the annual monitoring surveys and the catches obtained later in the same year has been assembled. While there is a great scatter around the regression line, possibly partly due to differences in monitoring precision between years (see discussion above), the figure shown suggests a significant relationship between both variables. The quota estimate for all these years was included when the fishery was opened and it is evident that catches taken were in most cases far higher (2-3 times) than the quota that would have been recommended using the reasoning of this study. This, however, is not the case for the years 2007 and 2008, when less sea cucumber were fished, than the quota would have allowed. We think that this discrepancy is due to great overestimates of mean pre-fishery stock densities in these years (through which too high quota were negotiated).

The often heard statement by the fishing sector that sea cucumber densities are higher in deeper waters giving the stock a strength in reserve if fishing pressure in shallower waters is high, could clearly be shown to be wrong for the year 2009, and also for the combined data of the eight year's period. This is an important finding of our study since it removes the basis for the argument that a large portion of the stock is out there in deeper waters where it can not be caught.

We believe that the monitoring and management strategy of the Galapagos sea cucumber stock that has been presented in this paper is an important step towards a sustainable fishery of this species. It is the first time that the attempt was made to estimate the size of the whole fishing area and of the fishable stock. Moreover, the monitoring was adapted to specific conditions (size and sea cucumber patchiness) of each macrozone, and the quota was made a fraction of the stock size (12.2%), which makes it adaptive to natural inter-annual stock fluctuations.

As a future step it may be considered to look for spatially-explicit tools for management of the Galapagos sea cucumber such as the implementation of territorial use rights (Defeo & Castilla 2005) or rotational closures of different areas from year to year. The first seems difficult in Galapagos because there are more fishermen with licenses than active fishermen and stock productivity is not evenly distributed over the different macrozones and also seems to vary spatially and temporally, which makes difficult a possible distribution of sub-areas to fishermen groups. The latter, however, seems a viable approach and our study provides a good basis through the classification and delimitation of macrozones and the estimation of their relative contribution to the overall stock. Closing macrozones completely for the fishery over a longer period of several years, would allow for a substantial stock rebuilding, and fertilization success should increase in these higher density areas and population wide recruitment may result. While this paper is being written, the National Park of Galapagos and the Charles Darwin Foundation are preparing for a pilot project for stock enhancement of the Galapagos sea cucumber through the collection of wild larvae in areas closed to the fishery. If successful, this project would allow for an acceleration of the stock rebuilding process.

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RESUMEN

Este artículo analiza la pesquería del pepino de mar en Galápagos, durante la década pasada y se estudian las razones de su difícil manejo y la sobre-explotación crónica. El objetivo principal de este trabajo fue proponer una estrategia mejorada para estimar el tamaño poblacional y el potencial de captura. Se definieron 15 macrozonas, y para ello se tomó en cuenta la distribución histórica de la flota pesquera y los resultados de prospecciones pesqueras pasadas. Las respectivas áreas fueron estimadas desde la línea de costa hasta la isobata de los 30m. El número de réplicas de muestreo por macrozona fueron calculadas para estimar la densidad poblacional con una precisión del ±25%. El tamaño poblacional total fue calculado sumando

la densidad poblacional de todas las macrozonas, luego el resultado fue multiplicado por 0.122 para obtener la cuota anual de captura. Este factor de multiplicación fue derivado mediante la fórmula de Cadima, en la cual se consideró una tasa de explotación (E) de 0.3 y una tasa de mortalidad natural (M) de 0.17. Estos resultados permitieron obtener una estimación precautoria y más conservadora de la cuota total de captura. La densidad poblacional pre-pesquería en 2009 estuvo por debajo del punto de referencia límite establecido, en consecuencia fue declarada en veda. Las densidades poblacionales promedio fueron significativamente menores a profundidades mayores a los 15m, contrario a lo esperado por los pescadores. A través de una regresión empírica entre el logaritmo de la densidad poblacional pre-pesquería y la subsecuente cuota de captura anual para el periodo 1998-2008, se descubrió que las capturas totales en la mayoría de los años han excedido la cuota de captura propuesta en este artículo, lo que explica el estado actual de este recurso, el cual se encuentra colapasado.

Palabras clave: Galápagos, invertebrados, sobre-pesca, cuota, pepino de mar.

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